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Contents

16. The Interaction of Large Space Structures with the Near-Earth Environment

by

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1. INTRODUCTION

The interaction between natural plasmas and satellites orbiting the planets is one aspect of the more general problem of the interaction between collisionless plasma flows and bodies in the solar system. Examples of body-plasma interactions relevant to the solar system are given in Table 1. The detailed structures, that is, the detailed particle and field distributions in space and time around the bodies, are expected to differ for different types of interactions. However, the basic patterns could be similar since the basic physical processes acting in such interactions are probably similar. Planetary magnetospheres and shocks for example are to be seen as effects whose cause is the interaction between the body (planet's intrinsic and/or induced magnetic field) and plasma (solar wind).

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Table 1. Examples of Body-Plasma Interactions in the Solar System

(A)	(1) Solar wind with planetary magnetic fields (for example, Earth).
	(2) Solar wind and a planetary ionosphere (for example, Venus).
	(3) Solar wind with non-magnetized bodies (for example, the Moon).
(B)	Planetary magnetospheres with natural satellites (for example, Jupiter/Io, Saturn/Titan).
(C)	Solar wind with comets.
(D)	Dust particles of different size and origin with the interplanetary medium.
(E)	Artificial satellites and large space platforms with planetary ionospheres/ magnetospheres, and with the solar wind.

The interaction yields cavities whose structure is quite complicated even for bodies that do not have an intrinsic magnetic field. Potential and density gradients, plasma oscillations and instabilities are created around the body. Acceleration mechanisms and time dependent phenomena are most probably responsible for various structural patterns that exist in the wake and elsewhere around the body. In a more general way, the question of the filling of the wake can be viewed as an example of an "expansion of a plasma into a vacuum".

For bodies having an intrinsic magnetic field (such as the Earth, Jupiter, and Saturn) or bodies having an atmosphere/ionosphere (for example, Venus), shocks ahead of the "body" are known to exist. In solar-planetary interactions the wake zone is often referred to as the "night-side"; "dark-side", "shadow-zone", or "anti-solar region".

Problems involved in body-plasma interactions extend to astrophysical plasma physics where the "body" may be a system and the "flow" is the galactic medium. Basic physical processes relevant to body-plasma interactions within the solar system could apply to larger cosmic systems. However, such an assumption should be tested and verified both theoretically and experimentally. Hence, it is quite clear that the complex problems involved in body-plasma interactions are of basic importance to space plasma physics.

Sound scientific work in this area will require in-situ experiments, laboratory simulations, and theoretical work. It would be most effective if these efforts were conducted simultaneously. Space geophysicists in the U.S.A. in the last two decades have devoted very little effort to the systematic study of body-plasma interactions for a variety of body and plasma parameters. This is true even for the more practical and specific case of satellite-ionosphere/magnetosphere

interactions. With a little extra experimental effort and cost, artificial satellites could have been instrumented to yield important information relevant to body-plasma interactions (Table 2). In the past the interest in satellite-ionosphere and satellite-magnetosphere interaction was restricted to spacecraft charging and, to a lesser extent, to wake and sheath effects. While the latter has practical (technological) applications to measurements performed by probes mounted on rockets and satellites, a wider view could have been adopted combining technological and scientific objectives simultaneously. It is perhaps ironic that even for the practical case of wakes and sheaths around probes and satellites orbiting in the terrestrial ionosphere, there are important questions that are not yet answered in a physically meaningful way.

Table 2. Aspects of the Interaction Between a Satellite and the Terrestrial Ionosphere

(1) Per se.
(2) As a "model" for various aspects of the interaction between planets and the solar wind and particularly between natural satellites with planetary magnetospheres (utilizing the concept of "qualitative scaling").
(3) As a test of the validity, quality, and range of applicability of thermal particle and field measurements performed in-situ.
(4) In the context of spacecraft charging.
(5) For testing theoretical models (physical assumptions and mathematical procedures).

The advent of the Shuttle with its wide range of capabilities provides a long awaited opportunity to perform controlled and carefully conceived in-situ experiments on "body-plasma" interactions that are of both scientific and technological interest, supported by laboratory and theoretical simulations. The technology being developed for advanced missions offers opportunities not readily available in the past two decades of space exploration. The author and N.H. Stone[1] have discussed new experimental approaches applicable for the Shuttle era. While it remains surprising that space geophysicists did not emphasize this area of scientific and technological endeavor in the past, it is possible now to utilize the

1. Samir, U., and Stone, N.H. (1980) Shuttle era experiments in the area of plasma flow interactions with bodies in space, Acta Astronautica.

Spacelab as a near-earth plasma laboratory and launch an extensive scientific and technological program of investigation. Experimental work, both in-situ and by laboratory simulation, together with a theoretical effort, should take place.

Capabilities such as tethered satellites, small throw-away detector packages and plasma diagnostic packages mounted on remote manipulators or booms could be utilized. In this way the scope of the investigations can be significantly expanded to encompass a wide range of questions relevant to the interaction of large bodies, that is, large space structures, in space.

The preliminary stage preceding such a scientific and technological program is the quantitative determination of the Spacelab environment and its charging effects. This stage is now in progress, and preliminary results were already discussed in this meeting, by Banks and Raitt, and by Shawhan and Murphy. It should be re-emphasized that it is possible to perform experimental work of both scientific and technological interest simultaneously, and that such an effort should be supported by an extensive theoretical effort.

2. DISCUSSION OF RESULTS

2.1 Morphological Studies

We restrict the discussion to satellite-ionosphere interactions and focus on results from parametric in-situ and theory-experiment investigations. In recent years the study of the distribution of thermal ions and electrons around ionospheric satellites focused on parametric rather than morphological investigations. The parametric studies were supported by a theoretical effort aiming at testing the validity and range of applicability of assumptions used in the theoretical models. Results regarding earlier theory-experiment comparisons are given in Gurevich and Dimant,[2] Al'pert,[3] and Samir and Stone.[1] The measurements used in recent studies came from the NASA Atmosphere Explorer C and E satellites and from the U.S.A.F. satellite S3-2. Results of such studies were used by Whipple[4] and by Garrett[5] in reviewing the present knowledge of spacecraft potential and charging mechanisms.

2. Gurevich, A.V., and Dimant, Ya.S. (1975) Flow of a rarefied plasma around a disc, Geomagnetism and Aeronomy 15(2):183.
3. Al'pert, Ya.L. (1976) Wavelike phenomena in the near earth plasma and interaction with man made bodies, Handbuch der Physik S. Flugge, Ed., Geophysics III V:217.
4. Whipple, E.C. (1981) Potentials of surfaces in space, Rep. Prog. Phys. 44:1197.
5. Garrett, H.B. (1981) The charging of spacecraft surfaces, Rev. Geophys. Space Phys. 19(4):577.

From basic measurements of ion and electron densities, temperatures, and the values of spacecraft potential with respect to local ambient, it was possible to obtain plots of the angular distribution of charge and potential around the spacecraft at fixed distances from the surface of the spacecraft. Information on ion mass allowed the current and potential around the satellite to be examined vs ionic Mach number. Some examples are shown in Figures 1 through 4.

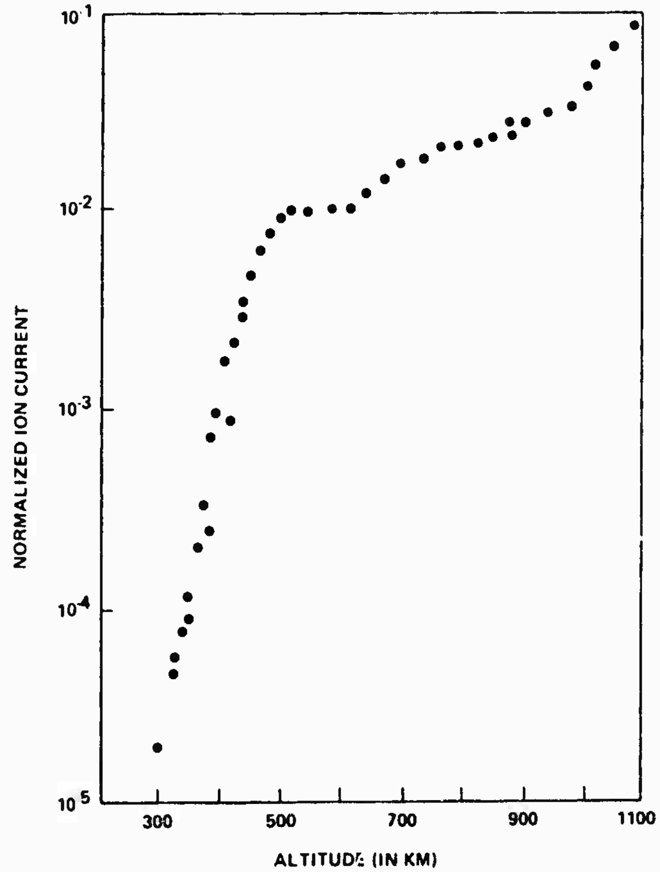


Figure 1. The Variation of Normalized Ion Current α = [I_+ (wake)/I+ (front)] With Altitude in the Altitude Range 300 to 1100 km (S3-2 Measurements)

As seen in Figures 1 and 2, and, as could have been expected, the ion depletion in the wake is more severe than the electron depletion. Hence, the wake region behind the satellite is depleted unequally of both ions and electrons. A

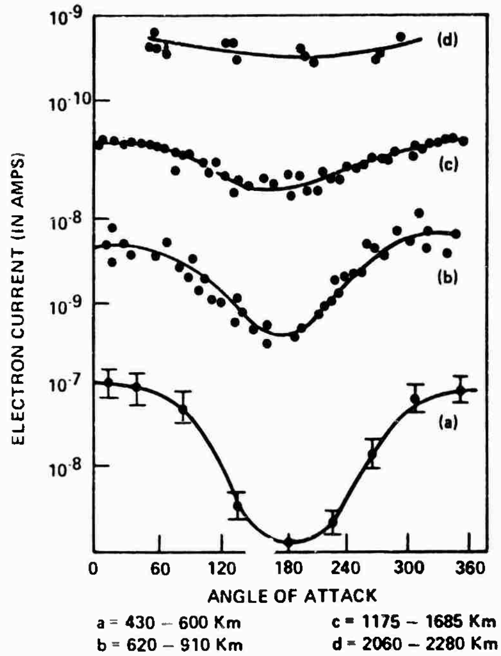


Figure 2. Variation of Electron Current (in Amperes) With Angle of Attack (θ) for the Altitude Ranges: (a) 430 to 600 km, (b) 620 to 910 km, (c) 1175 to 1685 km, and (d) 2060 to 2280 km Based on the Ariel I, Explorer 31, and Atmosphere Explorer C Measurements

negative potential well is thus created that acts selectively on the electrons and the ions.

Often, the practical problem of computing the spacecraft potential is solved by assuming that the potential distribution in the wake does not affect the total ion collection since most of the ions are collected by the front part of the moving body. While this can be considered as a reasonable zeroth approximation for ion collection it is not valid for electrons. Nor is it valid for ions if plasma oscillations and instabilities are indeed generated in the edges of the wake and ion acceleration mechanisms contribute significantly to the wake filling process. Theoretical evidence that supports the existence of instabilities in the wake boundaries was given by Gurevich et al,[6] Gurevich and Pitaevsky,[7] Al'pert[3] and

6. Gurevich, A.V., Pariskaya, L.V., and Pitaevsky, L.P. (1973) Sov. Phys. JETP 36(2):274.

7. Gurevich, A.V., and Pitaevsky, L.P. (1975) Non-linear dynamics of a rarefied ionized gas, Prog. Aerospace Sci. 16(3):227.

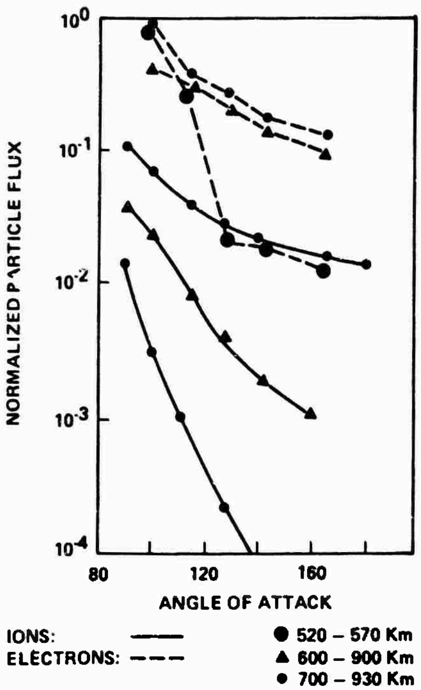


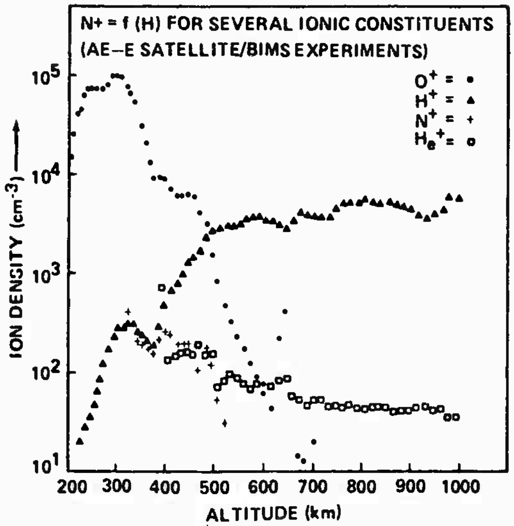
Figure 3. Variation of Normalized Ion and Electron Currents With Angle of Attack. Ions-solid line, electrons-dashed line for the altitude ranges: 520 to 570 km (●); 600 to 900 km (Δ); 700 to 930 km (·), based on Explorer 31 and Atmosphere Explorer C measurements

more recently (though in a different context) by Singh and Schunk.[8] Singh and Schunk studied the collisionless expansion of an H^+ - O^+ plasma into a "vacuum" because of its relevance to the polar wind, but this problem is similar in principle to that of an expansion of a plasma into the wake zone of any large structure orbiting in the near-earth environment or the "night-side" of a planet or moon that does not have a significant intrinsic magnetic field (for example, our moon, Venus).

Figure 3 shows the variation of normalized ion current $[I_+ (\theta)/I_+ \text{(ambient)}]$, and normalized electron current $[I_e (\theta)/I_e \text{(ambient)}]$ in the wake of the Explorer 31 satellite.[9] These variations are shown for several altitude ranges. The

8. Singh, N., and Schunk, R.W. (1982) Numerical calculations relevant to the initial expansion of the polar wind, J. Geophys. Res. 87(A11):9154.

9. Samir, U. (1981) Bodies in flowing plasmas: spacecraft measurements, Adv. Space Res. 1:373.



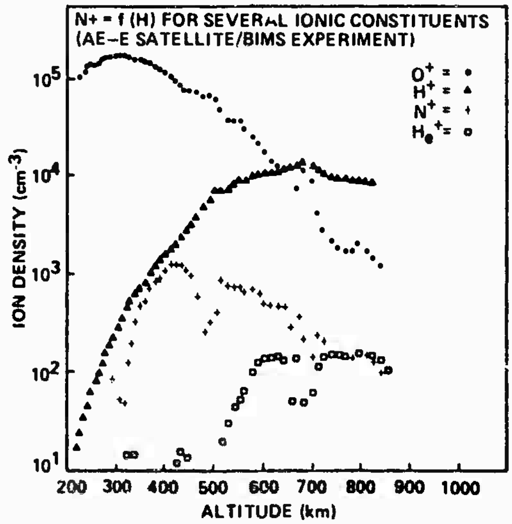


Figure 4. The Variation of Ion Density With Altitude for (O^+), (N^+), (H^+), and (He^+) Ions Based on AE-E Measurements

result shows quantitatively the difference between I_+ and I_e and, as expected (qualitatively) the difference increases as we proceed further into the wake region (that is, for larger values of the angle of attack θ). It is interesting to note that even close to the "terminator" ($\theta \sim 90^o$) the ion and electron currents differ appreciably.

2.2 Parametric Studies

To understand the physical processes involved in the filling-in of the wake region, and the structure of the near and far environment of the body (that is, the entire "sheath" zone), one must examine the variations of I_+, I_e, and $\phi = f(\gamma, \theta)$ with characteristic plasma parameters such as the ion-acoustic Mach number, average and specific ion composition, ratio of body-size to ambient Debye length, and spacecraft potential (with respect to local plasma potential). Examples of normalized current variation in the wake with average mass and ionic Mach numbers are shown in Figures 5 and 6.

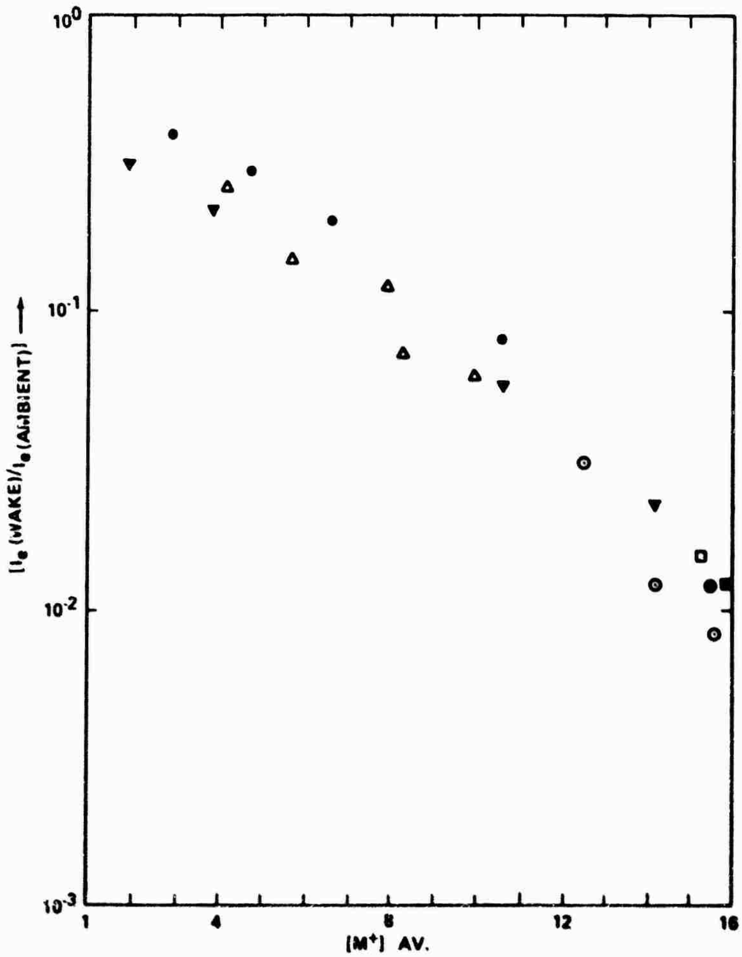


Figure 5. Variation of $[I_e\,(\text{wake})/I_e\,(\text{ambient})]$ With Average Ionic Mass $([M_+]_{av})$ Based on Measurements From the Explorer 31 Satellite

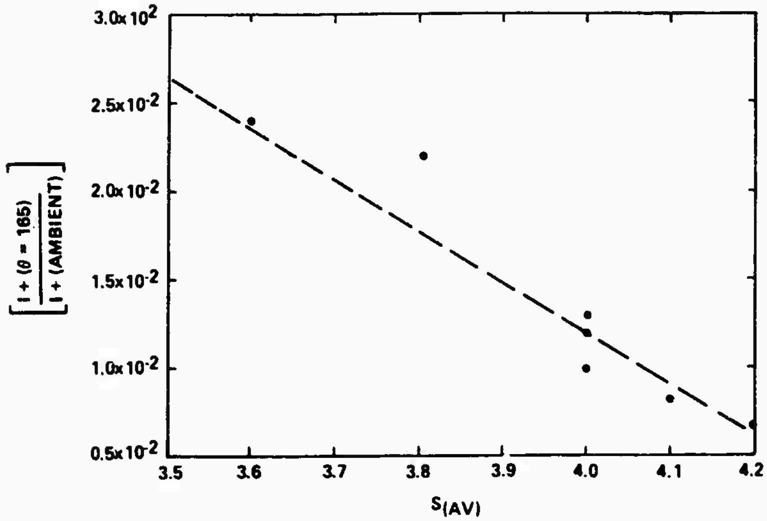


Figure 6. Variation of [I_+ (θ = 165°)/I_+ (ambient)] With Average Ionic Mach Number (S_{av}) Based on Measurements From the Explorer 31 Satellite

Surprising as it may be (and indeed it is!) the in-situ data available at the present time for the purpose of plasma-body interactions is meager, fragmentary, and restricted to the very near vicinity of the spacecraft. Obviously, this situation is not satisfactory. As mentioned earlier, this situation calls for new investigations utilizing the Shuttle/Spacelab facility, including capabilities such as tethered satellites, ejectable probe packages, and plasma diagnostic packages mounted and/or ejected from booms (for example, from remote manipulator-type arms). There can be no doubt that prior to relying on large space structures orbiting in space (space stations) as carriers of equipment of any kind, their entire interaction with the near-earth environment needs to be understood and known quantitatively. Experiments that have significance to both basic space physics and astrophysics should be conducted simultaneously (see Table 1).

Figure 7 shows the variation of normalized ion density [N_+ (θ = 160°)/N_+ (θ = 90°)] with R_D = Ro/λ_D. This result is based upon measurements by the Atmosphere Explorer C satellite and gives a quantitative measure of the importance of body size (R_o) normalized by the ambient Debye length (λ_D) in determining the amount of ion depletion in the wake (Samir and Stone[1] and the references therein). Ratios of $R_D \approx 2 \times 10^2$ are of scientific interest to a wide range of body-plasma interactions (see Tables 1 and 2) as well as to the interaction of large space structures with the terrestrial space plasma, another example of the possibility of combining scientific and technological objectives.

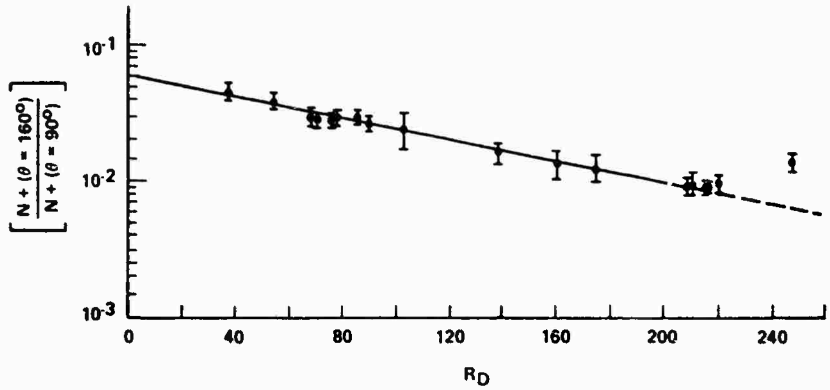


Figure 7. Variation of [N_+ (+160^o)/N_+ (ambient)] With Normalized Body Size ($R_D = R_o/\lambda_D$) Based on Measurements From the Atmosphere Explorer C Satellite

One more example of a parametric study is given in Figure 8. Here, the variation of [I_+ (wake)/I_+ (ambient)] is shown as a function of the electron temperature T_e for various values of the concentration ratio, [N (O^+)/N (H^+)]. While it is not the objective of this paper to go into detailed physical analyses, it is apparent that the above results are connected to the assumption of non-interacting streams filling in the wake zone.[3,6,7,10]

Among the more recent parametric studies performed by using relatively small samples of in-situ observations is the work of Samir et al,[11] which used measurements from the U.S. Air Force satellite S3-2. In this study it was possible to distinguish between the influence of normalized body size, $R_d = R_o/\lambda_D$ and normalized potential, $\phi_N = e\phi s/kT_e$, on the current ratio, α = [I_+ (wake)/I_+ (ram)], for the range $10 < |\phi_N| < 18$. However, uncertainty remains regarding the competition between R_D and S(H^+) and S(O^+), the oxygen and hydrogen ionic Mach numbers, respectively, in determining the distribution of ions near the satellite surface. From this investigation it became clear that care should be exercised in using the average Mach number, and average ionic mass, rather than using the specific ionic Mach numbers for each constituent.[11]

In summary, it is essential that parametric investigations be continued through both in-situ measurements and laboratory simulation work. Although

10. Gurevich, A.V., Pitaevsky, L.P., and Smirnova, V.V. (1969) Ionospheric aerodynamics, Space Sci. Rev. p. 805.

11. Samir, U., Wildman, P.J., Rich, F., Brinton, H.C., and Sagalyn, R.C. (1981) About the parametric interplay between ionic mach number, body-size and satellite potential in determining the ion depletion in the wake of the S3-2 satellite, J. Geophys. Res. 86(A13):11161.

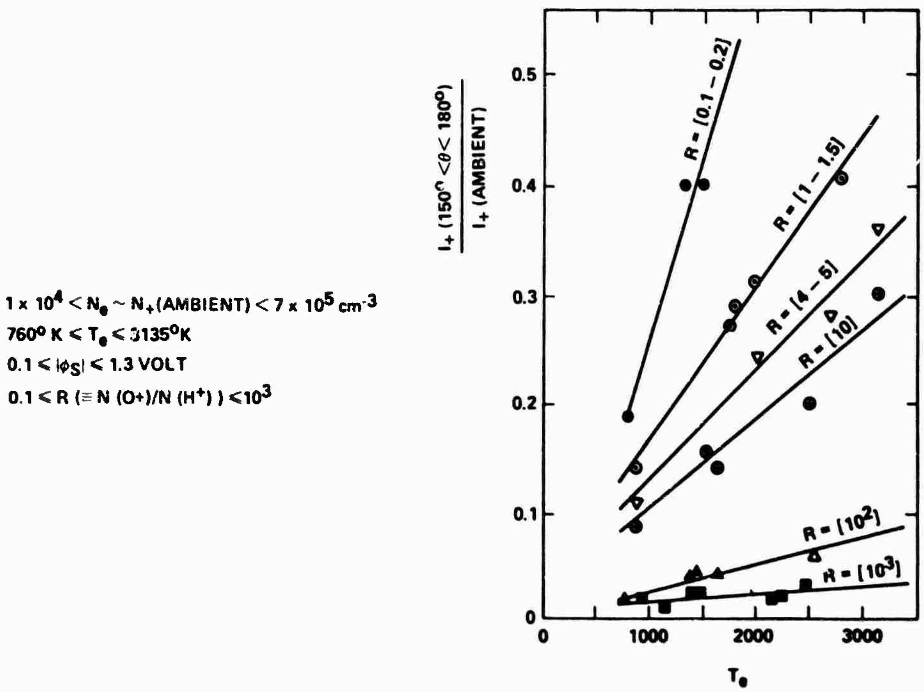


Figure 8. Variation of $[I_+ (150^{\circ} \leq \theta \leq 180^{\circ})/ I_+ \text{(ambient)}]$ With Electron Temperature (T_e) for Several Ratios of $R = [N (O^+)/N (H^+)]$ Based on Measurements From the Atmosphere Explorer C Satellite

the latter aspect was not discussed in the present meeting the importance of laboratory studies is eminent. The importance of laboratory studies regarding the "aerodynamics of bodies in a rarefied ionized gas with applications to spacecraft environmental dynamics" are discussed in Stone;[12,13] Stone and Samir;[14] and Stone, Samir, and Wright,[15] which also provide an extensive bibliography.

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12. Stone, N.H. (1981) The plasma wake of mesosonic conducting bodies, Part 1: An experimental parametric study of ion focusing by the plasma sheath, J. Plasma Phys. 25(3):351.

13. Stone, N.H. (1981) The plasma wake of mesosonic conducting bodies, Part 2: An experimental parametric study of the mid-wake ion density peak, J. Plasma Phys. 26(3):385.

14. Stone, N.H., and Samir, U. (1981) Bodies in flowing plasmas: laboratory simulation studies, Adv. Space Res. 1:361.

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2.3 Theoretical Studies

In addition to morphological studies (Figures 1 through 4) and parametric studies (Figures 5 through 8) theory-experiment comparison studies were also performed (see, for example, Refs. 10, 3, and 16). Discussions relevant to the latter in the context of spacecraft charging were given by Whipple;[4] Parker;[17] Garrett;[5] and to some degree by the S-cubed group and L. Parker in the present meeting.

Comparing theoretical models with experimental results (in-situ and laboratory) and different theoretical models among themselves is essential for determining the validity and range of applicability of physical assumptions used in the theoretical models. This is particularly so when very elaborate computer codes are used in solving the Vlasov-Poisson equations in a self-consistent manner for cases of interest to general wake studies and to spacecraft charging of large structures orbiting the earth.

In principle it makes no difference whether the structure of a wake is looked at as a problem of the expansion of a plasma into a vacuum, which is a basic problem of interest in space plasma physics and plasma astrophysics, or whether a more practical view is adopted for the purposes of spacecraft charging studies. Indeed, the boundary conditions are not the same; (because the surface properties at specific locations on the spacecraft, body geometry and so forth, differ) but in either case the same basic time-dependent Vlasov and Poisson equations should be solved in a self-consistent way.

Comparison of theoretical models with in-situ measurements for an (O^+) dominated plasma show a difference of at least 2 to 3 orders of magnitude for the maximum rarefaction zone on the wake axis. For several simplified models the discrepancy is even larger. Recent studies, for example, Samir and Fontheim,[16] have shown that even the use of the self-consistent steady-state computer code of Parker,[18] which solves the Vlasov-Poisson equations numerically, does not remove the discrepancy. An example of such a comparison is given in Figure 9 for $S_{av} = 7.7$; $\phi N\,[(e\phi s)/kT_e] = -8.4$, and $R_D = 162$. For this case, which represents a "large body" applicable to large structures orbiting in space, the measured value of $[I_+\ (\theta = 160)/I_+\ (\text{ambient})]$ exceeds the computed value by a factor of 600. It is reasonable to assume that for $[I_+\ (\theta = 180)/I_+\ (\text{ambient})]$, the discrepancy is even larger. The status of other theory-experiment comparisons is no better.

16. Samir, U., and Fontheim, E.G. (1981) Comparison of theory and in-situ observations for electron and ion distributions in the near wake of the Explorer 31 and AE-C satellites, Planet. Space Sci. 29(9):975.
17. Parker, L.W. (1982) Private communication.
18. Parker, L.W. (1976) Computation of Collisionless Steady-State Plasma Flow Past a Disc, NASA Report CR-144159.

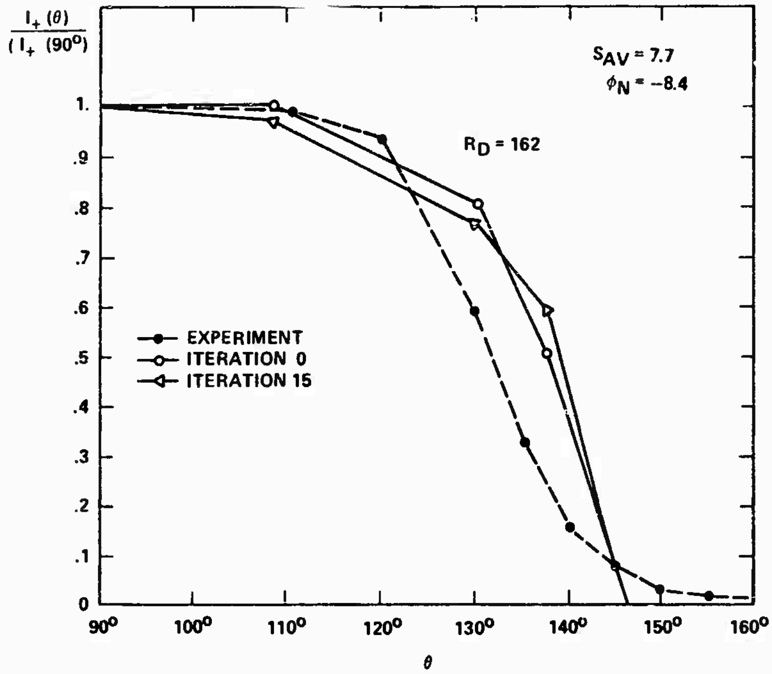

Figure 9. Variation of Computed and Experimental Values of $[I_+(\theta)/I_+(90)]$ With Angle of Attack (θ), for $90^o \leq \theta \leq 160^o$. The computations are based on Parker's model[18] and the measurements are from the Atmosphere Explorer C satellite. Iteration -0 refers to the "neutral particle" approximation

A similar conclusion is drawn from the comparison between theory and the Explorer 31 electron measurements, where the theory also significantly overestimates the electron depletion.[16] This suggests that the discrepancies may be due to the use of a steady-state theory and a single ion equation (using a mean ion mass). It was suggested that improved agreement between theory and experiment may be obtained by the use of the time-dependent Vlasov-Poisson equations with separate equations for the various ion species. Parker[17] believes that body geometry factors are responsible for the discrepancy. If Parker's steady-state model does not yield a better agreement for the maximum wake zone it is difficult to see how simplified models can be applied. Since plasma oscillations and instabilities can be generated by the motion of a spacecraft (or any other body in space) it is recommended that the theoretical models now being developed should attempt to solve the time dependent problem for several ionic species and for several values of the concentration ratio, $[N(H^+)/N \text{ (total)}]$.

Gurevich et al[6] and Gurevich and Pitaevsky[7] discussed the existence of strong acceleration of ions during the free expansion of a plasma. The application to the filling-in of the wake created in body-plasma interactions was specifically emphasized.

More recently Singh and Schunk,[8] discussed the characteristics of the expansion of a plasma into a vacuum and, like Gurevich et al, found it to be strongly dependent on the concentration ratio $[N(H^+)/N(O^+)]$ for an H^+ - O^+ plasma. In other words, it is of critical importance whether H^+ is a minor or a major constituent of the plasma. Both Gurevich et al[6] and Singh and Schunk[8] predict that upon the expansion of a plasma into a vacuum the ions are accelerated by a self-consistent electric field that arises during the expansion. The Russian computations (and similarly, those of Singh and Schunk) show that as a result of the acceleration a considerable portion of the light ions (for example, H^+ in an O^+, H^+ plasma) acquire energies on the order of 10^2 - 10^3 (kT_e/e). This implies that even if the H^+ relative concentration in the plasma is very small, these ions contribute significantly to the distribution of charge and potential in the wake region. Therefore, it is possible that zeroth approximation calculations of current collection for spacecraft charging may not be practically applicable. It is the author's impression that except for Gurevich et al,[6] and more recently Singh and Schunk,[8] who emphasized the importance of such an accelerating mechanism to space plasma physics, the computer codes written for wake theory in the context of the natural charging of satellites and large structures in space have not taken notice of this physical process. If, as predicted by Gurevich et al, the average energy of the H^+ ions on the boundary of the quasineutral zone behind the body for $[N(H^+)/N\ (\text{total})]$ is about (5 to 8) kTe/e (that is, energies of the order of 1 to 1.5 eV), then this process cannot be ignored.

Singh and Schunk[8] state in their paper that they are studying numerically the collisionless expansion of an H^+ - O^+ plasma into a vacuum because of the relevance to the polar wind. They suggest that the energization of ionospheric ions through the process of plasma expansion could be one of the mechanisms for creating the energetic ion population of ionospheric origin in the magnetosphere.

Again, we see that studying the complex of phenomena involved in the interaction between a large structure orbiting in space motivated by practical objectives may reveal physical processes that are of a much wider range of interest.

Now, with the advent of space shuttle, such studies can be performed in a controlled way for the benefit of both science and technology.

Acknowledgment

I thank Nobie Stone and Ken Wright for reading the paper and for their comments. This paper was written while the author was a senior NRC associate at the Space Science Laboratory, NASA/MSFC, Huntsville, Ala.

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